Path integration following temporal lobectomy in humans

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Received 1 February 2000; received in revised form 23 October 2000; accepted 1 November 2000

Abstract

Path integration, a component of spatial navigation, is the process used to determine position information on the basis of information about distance and direction travelled derived from self-motion cues. Following on from studies in the animal literature that seem to support the role of the hippocampal formation in path integration, this facility was investigated in humans with focal brain lesions. Thirty-three neurosurgical patients (17 left temporal lobectomy, LTL; 16 right temporal lobectomy, RTL) and 16 controls were tested on a number of blindfolded tasks designed to investigate path integration and on a number of additional control tasks (assessing mental rotation and left–right orientation). In a test of the ability to compute a homing vector, the subjects had to return to the start after being led along a route consisting of two distances and one turn. Patients with RTL only were impaired at estimating the turn required to return to the start. On a second task, route reproduction was tested by requiring the subjects to reproduce a route consisting of two distances and one turn; the RTL group only were also impaired at reproducing the turn, but this impairment did not correlate with the homing vector deficit. There were no group differences on tasks where subjects were required to reproduce a single distance or a single turn. The results indicate that path integration is impaired in RTL patients only and suggest that the right temporal lobe plays a role in idiothetic spatial memory. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Dead reckoning; Spatial memory; Spatial navigation; Temporal lobes

1. Introduction

The hippocampal formation has been a major interest within neuropsychology over many years, with cross-species evidence for this structure providing at least part of the neural basis for memory and learning. One particular aspect that has been investigated is the ability to navigate around the environment. Spatial navigation involves at least two processes; firstly, determining the direction and configuration of landmarks in the environment to estimate position (cue-based navigation); secondly a dead reckoning process in which self-motion (idiothetic) signals are used to determine current position and/or a homing vector. The latter, termed path integration, involves determining position information on the basis of internal feedback mechanisms about how far and in what direction one has moved.

Until recently, research linking navigation to hippocampal function has focused largely on cue-based navigation. This research was stimulated, in part, by the theory proposed by O’Keefe and Nadel (1978), in their book ‘The Hippocampus as a Cognitive Map’ (see also Refs. [49,53] for reviews). This suggests a hippocampal based system in which spatial information is integrated into a viewer-independent (allocentric) representation, in the form of a cognitive map. Wide support for the hippocampus being involved in spatial orientation comes from different species of animals. In rodents, place cells have been discovered in the...
hippocampus, firing when the animal is in a particular location [46,56,58,59]. Bilateral lesions to the hippocampus also result in spatial memory impairment [54]. Similarly, place cells have been identified in monkeys, but also, more numerous are cells that respond to location of view of the monkey irrespective of their position [66].

In humans, there is also wide support for the role of the hippocampal formation in spatial memory. Evidence points to a functional dissociation between the left and right mesial temporal lobe structures. The left (dominant) sided structures have been found to be important for verbal memory and learning [29,57], whilst those on the right (non-dominant) are implicated in spatial memory [1,19,34,35,51,52,67]. In humans, the cognitive mapping theory has been modified such that the right hippocampus subserves a mapping system similar to that proposed in animals.

A further process, path integration, has been shown to aid the return to a given location [32]. The animal keeps track of the outward journey, either by using signals that are entirely self-generated during locomotion (idiographic cues), or using external landmarks or directional references, such as the sun (allothetic cues). It has been proposed that information about homeward direction and distance is maintained by a continuous integration (summing) of moment-to-moment changes to update the position relative to the starting location, enabling the animal to return along the shortest path [21]. Homing strategies based on this route-based information processing (termed path integration) have been studied in a range of arthropods and vertebrates [15].

There are several idiothetic or self-motion cues that provide the information required to update position information. Vestibular signals, which are generated by accelerations of the endolymph in the otoliths and semicircular canals, provide information about linear and angular acceleration. Somatosensory information (from pressure changes on the skin and proprioceptive reaferences from the muscles, tendons and joints) as well as stored motor commands (efference copies) complement vestibular information in the estimation of rotations as well as translations. The relative contributions of vestibular and somatosensory information to the estimation of rotations and distances have been studied in rodents [16,43] and humans [11,23,25,26,28,30,31,64,65,68] by comparing performance on active and passive transportation tasks, in the estimation of rotations and translations. The importance of vestibular inputs have also been examined in rats by lesioning the vestibular end organs and more central vestibular relay stations [42,60], and in humans by using subjects with labyrinthine damage [41], and also through neuroimaging [71].

Support for hippocampal formation involvement in path integration has come from a number of sources, and existing data have been reinterpreted in this fashion. For example, it has been found consistently that place fields are not dependent on the continued visibility of landmarks, being largely preserved if landmarks are removed in the animal’s presence [48,55] or if the light is extinguished [37,39,61]. This can be interpreted as indicating that the response of place cells can be related to the position of the animal within the environment. Additionally, it has been observed that in the Morris Water Maze, rats with Fornix-Fimbria (FF) or hippocampal lesions cannot learn to swim to new ‘hidden’ locations, interpreted as indicating that they are unable to use path integration [74,76,77]. Whishaw and colleagues have carried out a series of experiments [33,74,79] in which FF-lesioned rats [75,79] and those with selective hippocampal lesions [33] failed to learn to return to hidden locations using self-movement cues whilst swimming, foraging or following a scented string.

In contrast to the growing number of animal studies investigating the role of hippocampus in path integration, there have been no studies in humans to date. The following experiment was designed to investigate the role of the left and right temporal lobes (including the hippocampal region) in path integration in humans. Subjects who had a selective unilateral resection of the temporal lobe for the treatment of intractable epilepsy were compared with a matched control group, on a series of tasks. Given the established pattern of functional lateralization in humans, as indicated by previous studies of spatial memory [1,19,34–36,45,51,52,67], it was predicted that lesions of the right (non-dominant) temporal lobes would be associated with a path integration deficit, but subjects with left-sided damage would be unimpaired.

In the following study, path integration was explored using methods similar to that of Loomis et al. [31], with two main types of tasks. The first, requiring the computation of a homing vector, involved the subjects being blindfolded and led along a predetermined path, having then to return directly to the starting place. This was compared to a route reproduction task in which the subject was again led blindfolded along a particular path and then simply had to reproduce this route. In each case, the subjects were relying on idiothetic cues to navigate around the environment and had to hold or integrate directional and distance information in order to perform the tasks successfully. To assess the component aspects of these tasks, subjects also performed two simple tests in which they had to reproduce either a simple turn, or a simple distance on which they were led. An additional set of control tasks were implemented in order to test whether some of the prerequisite abilities necessary for path integration were intact, including spatial manipulation and judgement of distances and turns.
2. Method

2.1. Subjects

2.1.1. Temporal lobectomy patients

The study included 33 patients who had undergone a unilateral temporal lobectomy for the treatment of intractable complex partial epilepsy. These consisted of 17 left temporal lobectomy (LTL: eight males, nine females) and 16 right temporal lobectomy patients (RTL: seven males, nine females). The standard en bloc resection [17] was conducted. This involves removal of between 5.5 and 6.5 cm of temporal lobe tissue from the anterior pole in the posterior direction, with sparing of the superior temporal gyrus in the language dominant hemisphere. Additional mesiotemporal structures are removed, including the amygdala and approximately two-thirds of the hippocampus.

Patients were included only if they displayed evidence of left-hemisphere language dominance, as demonstrated through the intracarotid sodium amytal test, conducted preoperatively [68,72], or they were righthanded. Additional exclusion criteria were evidence of a current psychiatric illness, additional neurological problems, and a low intelligence quotient (<75, Wechsler Adult Intelligence Scale — Revised) [73]. Subjects under the age of 16 or over 60 years of age were also excluded. All patients were under the care of Professor C. E. Polkey (Academic Neurosurgery, King’s Neuroscience Centre, London).

2.1.2. Healthy controls

Sixteen healthy controls (seven male, nine female) were tested.

2.1.3. Subject characteristics

All groups were matched for age, with an analysis of variance revealing no significant difference in age between groups. The mean ages in years were LTL: 35.8 (S.D. 10.59); RTL: 38.8 (S.D. 8.42); and controls: 38.4 (S.D. 10.6). Seizure control at the time of testing was established according to Engel’s classification [13], with approximately similar numbers in class I (6 LTL, 8 RTL), II (3 LTL, 2 RTL), III (5 LTL, 5 RTL) and IV (2 LTL, 2 RTL). In the control group, IQ was estimated using the National Adult Reading Test — Revised (NART-R) [50]. In the patient group, IQ was measured at a previous assessment using the Performance IQ (PIQ) scale of the Wechsler Adult Intelligence Scale — Revised (WAIS-R) [73]. The mean IQ was 103.38 (S.D. 17.08) in the LTL group, 97.13 (S.D. 17.02) in the RTL group and 106.75 (13.10) in the control group. There was no significant difference between the groups in IQ.

2.2. Procedure

2.2.1. Equipment

The experimental tasks were conducted in an unlit room, 7.1 m × 5.9 m. In all tasks, the subjects wore a blindfold and sound-attenuating headphones. Mounted on top of the headphones was a 9 V bulb that was connected to a battery pack that subjects placed in their pockets or clipped to a belt. During the locomotion tasks, the light from the bulb was tracked by two cameras set 1.7 m from the ground in two corners of the room 5.9 m apart. The two cameras were connected to a computer that recorded the angular position of the bulb from each camera and analysed this data to determine the coordinates of the subject during each frame.

2.2.2. Homing Vector Task

The aim of this task was to test the ability to integrate idiothetic information about distance and direction travelled to determine a homing vector. The subjects were led (blindfolded) along two sides of a triangle, and they then had to return to the starting position (see Fig. 1).

Ten different triangles were used. To guide the experimenter, fluorescent markers were placed on the floor at

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1 Ethical approval from the relevant institution was sought and obtained for the recruitment and testing of subjects undertaken in the present experiment.
approach to signify the triangles. Each route consisted of two legs, with the same start and end point (2.5 m apart) but with varying turn positions. The required turn to return to the start was 90, 120 or 150, −90, −120 or −150°. The second leg was either 1 or 2 m long, and the first leg was 1.2, 1.7, 2.2, 2.3 or 2.7 m long. Two pseudo-random orders of trials were used, with alternate subjects allocated a particular order of trials. The subjects were led from the start to a numbered turn point, and then turned and led towards the end of the second leg (Fig. 2). On reaching this point, the subject was required to turn towards the start point and attempt to walk back to the start. Between trials, subjects were led on a circuitous route to prevent them getting feedback about their accuracy.

2.2.3. Route reproduction
The aim of this task was to assess the ability to hold in memory a route that was processed on the basis of idiothetic cues. The subject was moved along two legs of a triangle and then had to reproduce the same movements (see Fig. 3). Before setting off to reproduce the two sides of the triangle, the subjects were turned by their shoulders to face back into the room to give them space to complete the task. Turning the subjects made it more difficult for them to utilize a map-based approach, thus placing greater emphasis on egocentric encoding. The instruction given to the subject was to imagine they were back at the start point and to reproduce the journey on which they had just been led.

2.2.4. Turn reproduction
The aim of this task was to assess the ability to estimate body turns on the basis of idiothetic cues. The subject had to move forward blindfolded and was turned. They then had to move forward (two steps), reproduce the turn, and move forward again (two steps) (see Fig. 4). Subjects were required to reproduce 12 different turn angles.
Fig. 5. Distance reproduction. The subjects are led forward $x_1$. They then reproduce the distance (indicated by $x_2$).

Markers were arranged to give 12 angled lines, of 150, 120, 110, 90, 84, 45, −150, −120, −110, −90, −84 and −45°. These angles were chosen as they were approximations of either the angle needed to create a homing, or the angle to be reproduced on the route reproduction task (described below).

2.2.5. Distance reproduction

This task was used to assess the ability of subjects to reproduce distances previously travelled, sensed only through idiothetic cues. The subjects moved forward a specified distance, turned 180° to face the start and were then required to reproduce the distance by walking back to the start. Three different distances were used (1.5, 2.5, and 3.5 m), and a total of ten trials (three or four trials of each distance) were given in one of two pseudo-random orders (see Fig. 5).

2.2.6. Additional procedural information

The subject repeated a single number between 1 and 10 throughout each task, selected at random for each trial. This was to prevent the subject from counting time or footsteps, the rate being set to be faster and out of phase with their footsteps, a method found in pilot studies to be an effective way of preventing counting with minimal executive load [6]. The subjects held onto a short pole (0.5 m). For the turn reproduction task, the pole was held at one end, close to the body, with the pole pointing away from the body (to make it easier to rotate the subject accurately). In the other tasks, the pole was held with one hand at each end and parallel to the line of their shoulders. On each task, the subject was guided by the experimenter, who moved the pole, held by the subject. Fluorescent markers were placed on each of the subject’s feet and on the pole to allow accurate positioning of the subject. On each task, the command ‘Go’ was given at the start, “Turn” was given when the subject was to be turned, and ‘Stop’ when they had to stop. The experimental tasks were performed in same order for each subject, to ensure that possible fatigue or practice effects were constant across subjects. The order was as follows: (1) Turn Reproduction; (2) The Homing Vector Test; (3) Route Reproduction; and (4) Distance Reproduction. Subjects were questioned after the experimental tasks to ascertain what strategies they had used.

2.2.7. Movement recording

Inspection of the data revealed three types of errors: (1) Erroneous camera recording (a problem also encountered by Loomis et al. [31]), was mainly caused by the light not being detected by the cameras, often at the end of a trial. In cases where it was clear that the subject had already finished (the subject had stopped or significantly slowed their movement), the last recorded position was taken to be the final position, and these trials were included; (2) Demonstration errors where the route demonstrated by the experimenter was incorrect were discarded. 1.89% of trials were discarded because of (1) or (2); and (3) Turn Reversals in which the subject turned the wrong way on 15.92% of route reproduction trials and 6.83% of turn reproduction trials.

The proportion of such errors was compared across subject groups, using a non-parametric Kruskal–Wallis test. On route reproduction, there was no group effect of turn reversals. On turn reproduction, the groups differed significantly ($P < 0.01$) in turn reversals, with superior performance in the control group compared to the two patient groups. Reversal trial data were discarded because it was not known a priori whether turning the wrong way was independent of estimating how far to turn (on turn reproduction and route reproduction), or what distance to walk (on route reproduction), so that including this data could have confounded the results. This is unlikely to influence interpretation of the results, as there was no significant difference in frequency of turn reversal errors in LTL and RTL groups. Although fewer control trials were omitted on turn reproduction, this bias would favour the patient groups, in which problem trials were removed. A correction was performed on each outcome measure within the experimental tasks (for each subject group separately), to remove outlying data four standard deviations above or below the mean. The percentage of total variables removed for each group was as follows: control, 6.25%; LTL, 6.05%; and RTL, 3.56%.

2.2.8. Subsidiary tasks

The following tasks were included in order to control for the possibility that factors other than the processing of idiothetic information (such as mental rotation or left–right orientation) could explain group differences on the experimental tasks. The subsidiary tasks were given after the experimental tasks, in a fixed order as
follows: Manikin Test, Benton’s Test of Left–Right Orientation, and Money’s Road Map Test.

2.2.8.1. *Benton’s Test of Left–Right Orientation* [9].
This test assesses left–right orientation and mental rotation. The subject was asked to sit facing the experimenter, and they were then asked a series of questions, such as ‘show me your right eye’, ‘touch your right ear with your left hand’, ‘point to my left leg’ and ‘put your left hand on my right shoulder’. If people have difficulty in identifying their own left or right body parts, this may indicate a general left–right orientation deficit. If they had difficulty in identifying the experimenter’s left or right body parts, this could be caused by a difficulty in mentally rotating their body image to match the experimenter’s direction (or equally in rotating the experimenter’s body to match their own).

2.2.8.2. *Manikin Test* [62,63]. This task assesses mental rotation. The subject was shown a set of 32 pictures of a man holding a ball with a vertical line in one hand, and a ball with a horizontal line in the other. The man was facing towards or away from the subject, and was upright or upside down. The task of the subject was to say which of the manikin’s hands was holding the ball with the vertical line. It is assumed that to identify the correct hand, mental rotation is needed, either of the image of the manikin, or the image of one’s own body. Deficits in mental rotation are usually associated with parietal damage [15,18,34,40,57], and it was not predicted that a deficit would be found in the temporal lobectomy patients.

2.2.8.3. *Money’s Standardized Road Map Test* [12]. This task also tests mental rotation (of the image of the subject’s own body) together with left–right orientation. The subject was shown a road map with a route marked on it and had to tell the experimenter which direction (left or right) they would have to turn at each bend in the route if they were to navigate the route correctly.

2.2.9. *Data processing*

The two cameras tracked the position of the light on top of the subject’s head, and the direction of this light in relation to the two cameras was used by the computer to calculate the coordinate position of the subject during each frame. This was based on the distance between the cameras, the angle of the light relative to the line joining the cameras, and the angle of the light in relation to the cameras directly. The data were geometrically corrected, giving the subject’s position in Cartesian coordinates.

In order to derive the relevant outcome measures (distances walked in Cartesian coordinates and angles turned in degrees), information about a number of positions within the routes was required. These were the start position, the turn position (where applicable), end of the led route position, and the final finish position. The program that processed the light position located the turn position by identifying the points of least velocity within the routes, and this indicated the other required positions, which had already been identified during testing by the computer operator. All routes and the key positions used to derive outcome measures were viewed and checked during this process, using a graphic library function. Subject routes for the Homing Vector Test trials were plotted using ‘SigmaPlot-4.0’, as an additional check on the validity of measurement (see Fig. 6, which shows the homing vector routes for one subject). The outcome measures were imported into ‘SPSS-7.5’ for statistical analysis.

3. Results

The principal outcome measure used on the experimental tasks was the unsigned percentage error, in which the produced turn or distance was expressed as an unsigned percentage of the required turn or distance. Thus, in the Homing Vector Test, Turn Reproduction and Route Reproduction, the turn error was the unsigned difference between the subject’s produced turn and the required turn as a percentage of the required turn. Similarly, the distance error on the Homing Vector Test, Distance Reproduction and Route Reproduction was the unsigned difference between how far subjects actually walked, and the required distance, as a percentage of the required distance. On Route Reproduction, the distance measure was represented by the first and second leg of the outbound or reproduced route added together. The Homing Vector Test included an additional measure, the end-point error,
which represented the Cartesian distance between the final stopping location and the required location (at the start position).

3.1. Results of experimental tasks

3.1.1. Homing Vector Test

The Homing Vector Test results are shown in Figs. 8 and 9. The analysis revealed a significant difference between groups \([F(2,48) = 5.787, \, P < 0.01]\) in the end point error (Fig. 7). Post-hoc least-squares differences (LSD) revealed that the RTL group were significantly impaired relative to controls \((P < 0.001)\), finishing further away from the goal position, and with the RTL group significantly worse than the LTL group in the predicted direction \((P < 0.05;\) one-tailed significance). There was no significant difference between the LTL and control group. Analysis of the turn error also showed a significant difference between the groups \([F(2,48) = 5.468, \, P < 0.01]\), which was caused by an impairment in the RTL group compared to controls \((P < 0.01)\) and LTL \((P < 0.05)\). There was no significant difference between the LTL and control group. Analysis of the distance error revealed no significant difference between the groups (Fig. 8).

3.1.2. Route reproduction

Analysis of variance of the turn error revealed a significant group effect \([F(2,38) = 5.888, \, P < 0.01]\), which was related to significant impairment in the RTL group compared to the control \((P < 0.01)\) and LTL group \((P < 0.05)\). There was no significant difference between the LTL and control group. The difference between the groups in their ability to reproduce the distance (distance error) was not significant (see Fig. 9).
One-way analyses of variance were used to examine the effect of gender on the outcome measures from all the experimental tasks, and these were not significant. The effect of IQ on performance was investigated by performing analyses of covariance comparing the groups on the outcome measures, with IQ as a covariate. This showed that IQ was not a significant covariate of performance on the experimental tasks, and hence the abilities measured by the experimental tasks appear to be independent of IQ. On post-experimental interview, none of the subjects claimed to have used vision or hearing to ascertain their position, and nearly all subjects claimed not to have tried or to have been unable to count their footsteps.

### 3.1.5. Subsidiary tasks

On Benton’s Test of Left–Right Orientation, the Manikin Test, or the Money Road Map Test, there were no significant group differences based on a one-way analysis of variance. Thus, the TL patients were unimpaired at tasks requiring left–right orientation or mental rotation, and the deficits in the RTL group on certain measures in the experimental tasks could not be attributed to a general difficulty in this domain (Table 1).

### 3.1.6. Relationship between performance on the Homing Vector and route reproduction tasks

The data were further analysed to explore whether the Homing Vector Test deficit in the RTL group could be explained by a difficulty in remembering the outgoing route rather than the ability to deduce a homing vector. If so, then this would predict an association between route reproduction and the ability to deduce the homing vector. Thus, for each group separately, the route reproduction outcome measures (turn and distance errors) were correlated with the Homing Vector Test outcome measures (end point error, turn and distance errors) using a Pearson correlation. None of these analyses was significant.

### 3.1.7. Error tendencies

In order to investigate whether there were any systematic tendencies in the data, for subjects to overshoot or undershoot on turns and distances, the signed turn and distance percentage errors were also examined. A negative value indicated an undershoot, and a positive value indicated an overshoot. Group differences were examined using one-way analyses of variance. There were no significant differences between the groups (signed percentage error), on the homing vector test, turn reproduction or distance reproduction tasks. On route reproduction, there were significant differences between the groups on the signed percentage turn error \(F(2,39) = 5.757, P < 0.01\), but not distance error. This was due to a greater tendency in the RTL group to overshoot turns.
overshoot on the turn, compared to the control ($P < 0.01$) and LTL group ($P < 0.01$) (based on LSD analysis). All subject groups tended to overshoot on the turn on route reproduction, as indicated by one-way $t$-tests (comparing mean values to zero) performed on each subject group separately (control: $P < 0.001$; LTL: $P < 0.001$; RTL: $P < 0.001$). Thus, the group differences on the signed percentage turn error may be explained by an overall impairment in the right temporal lobectomy group at estimating the turn together with a general tendency seen in all groups for overshooting. As there were no group differences in error tendencies on the other experimental tasks, over- and undershooting tendencies were determined using one-way $t$-tests on the mean signed percentage error for all subjects. On the Homing Vector Test, the mean signed percentage turn error was not significantly different from zero indicating no turn error tendency, but the mean signed percentage distance error was significantly positive ($P < 0.01$), indicating that subjects tended to overshoot the distance required to return to the start. On route reproduction, subjects tended to overshoot on the distance ($P < 0.05$) as well the turn (as indicated above). No error tendencies were seen on turn reproduction and distance reproduction.

### 4. Discussion

The aim of this study was to investigate the role of the human temporal lobes including the hippocampal formation in path integration, the process the deriving position information from idiothetic inputs. The analysis was performed on 49 subjects, 16 patients with left temporal lobectomy (LTL), 17 with right temporal lobectomy (RTL) and 16 matched controls. The findings of this study support a role for the human temporal lobes on tasks of path integration, and this function, like other mnemonic spatial functions appears to be lateralized to the right hemisphere.

On the homing vector task, which required subjects to return to the start after a blindfolded outbound journey consisting of two distances and one turn, the RTL group was impaired at returning to the start position (as measured by the distance of their final position from the start). This was related to impairment in estimating their direction and not their distance from the start. A RTL deficit in reproducing turns was found on the route reproduction task in which a route consisting of two distances separated by a turn had to be reproduced. There were no group differences in their reproduction of distances on this task. On the simple turn reproduction and distance reproduction tasks, in which turns or distances alone had to be reproduced respectively, no group differences were found. The results could not be accounted for by subject characteristics (IQ or age), or abilities in mental rotation or left–right orientation.

The current study indicates that the lateralization of spatial function in humans is not isolated to tasks involving the spatial layout of objects in the environment, but also includes non-visual navigational tasks using self-motion input. A hippocampal basis for path integration is not established precisely, because temporal lobectomy involves more widespread removal of brain tissue, including the anterior temporal lobe, the entorhinal, perirhinal and parahippocampal regions [44]. Thus, the importance of the right hippocampal formation in path integration remains to be determined through investigation of subjects with focal hippocampal lesions.

Path integration involves a number of processes, and extra-temporal areas are likely to be involved in some of them. For example, the processes required for deducing a homing vector may include (1) the establishment of an initial reference point; (2) the monitoring of the relevant self-motion inputs; (3) the processing of self-motion inputs to derive information about distance and direction travelled; (4) the integration of distance and directional information to derive a homing vector; and (5) a mnemonic component that stores ‘on line’ the outbound route and/or the distance and direction of the initial reference point relative to the animal’s current position (the homing vector). A number of models of path integration have been proposed [4,7,8], which vary in their view of the path integration process. One model is that path integration is a continuous process [8,21,43,47] such that at any point in time, a homing vector is available, and memory of the outbound route is not required. This could be achieved neuronally by the continuous computation of a motor program that would return the animal to the fixed goal [3,14].

### Table 1: Results of subsidiary tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Control Mean (SD)</th>
<th>LTL Mean (SD)</th>
<th>RTL Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benton’s Test of Left–Right Orientation</td>
<td>18.3 (2.1)</td>
<td>19.5 (0.7)</td>
<td>18.6 (2.2)</td>
</tr>
<tr>
<td>Manikin Test</td>
<td>27.9 (5.5)</td>
<td>29.8 (4.2)</td>
<td>25.9 (7.6)</td>
</tr>
<tr>
<td>Money’s Standardized Road Map Test</td>
<td>27.5 (5.6)</td>
<td>27.3 (5.2)</td>
<td>28.4 (5.0)</td>
</tr>
</tbody>
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other model is based on the assumption that the homing vector is derived at discrete points in time, such as the point of return, and that accurate path integration depends on the retention of the outbound route in memory [20,27,31]. A third model would draw on the cognitive mapping system proposed by O’Keefe and Nadel [55]. This predicts a more complex system of path integration, in which updating and mapping are supported by the same neuronal architecture. An example of this structure is the preconfigural network model of McNaughton et al. [38], in which an internal abstract representation is generated through self-motion. As the animal explores the environment, information becomes secondarily bound to this structure through associative learning. Here, in the absence of landmarks initially (for example, in darkness), an initial reference for path integration is set, which is independent of external cues. With this model, there is no need to retain the homing vector or outbound path, as a homing vector can be derived at any point in time from a continuously updated map, indicating the animal’s position in the environment.

In this study, the main finding with respect to path integration was that the deficit lay in the directional measure, but not distance. Previous studies by Berthoz and colleagues suggest that outbound distances and directions can be coded separately [10]. This in turn raises a number of issues in relation to interpreting the current results. In path integration, in order to compute the homing vector, the two types of information from the outward trajectories have to be “bound” in order to compute the final distance and direction. In this case, it appears likely that the originally encoded information was maintained sufficiently accurately to compute the final distance. Thus, the dissociation of the deficits would have to occur at the final stage, perhaps in encoding and maintaining in memory the return path direction. The ability to encode simple directional information (turn reproduction) in the RTL patients was not impaired, so this points towards difficulties with subsequent processing or representation. Our data are consistent with the view that the homing vector is derived at discrete points in time, in this case at the point of return, rather than on a continuous basis. If the homing vector were derived continuously, this model would predict that errors would accumulate on the distance, as well as the turn element of the task. As a caveat, the distance measure may have been less sensitive because the same return distance was used for each trial. Nevertheless, in the absence of feedback at the end of trials, this distance would still have had to be computed, even if some learning took place.

Klatzky and colleagues [27] have investigated the theory of path integration as a non-continuous process that utilizes outbound trajectories stored in memory. Evidence for this comes from examining the systematic response bias on path integration tasks. The finding that low values tended to be overestimated, and high values underestimated [20], a regression to the mean effect implies that the final trajectory has been computed at the point of return. Further evidence for this comes from Loomis et al. [32], who tested adventitiously and congenitally blind subjects and blindfolded controls on a number of tasks similar to the current tasks. Loomis et al. found that increasing path complexity was associated with increased return latency to return to the start, and they argued that if subjects integrated the route on a moment-by-moment basis, then the latency to begin walking back to the start would be the same, regardless of route complexity. However, Amorin et al. [5] have shown that subjects can be systematically cued either to remember the route or to update their direction, and this in turn can be verified by measuring their latencies either in the walk (which is thought to slow with updating) or the decision point at the end (thought to be reduced with route remembering). The methods used by Loomis et al. (with the subjects not knowing in advance whether they had to retrace a route or reproduce a homing vector) could have forced subjects to remember the outbound route and thus limited the continuous updating of position that might otherwise naturally occur.

As well as the path integration deficit, RTL subjects were impaired in their memory for the turn within a route (as assessed by route reproduction). Such memory impairment is not explained by impairment in encoding turns, because of the lack of deficit on the turn reproduction condition. It adds to a body of evidence indicating that spatial memory seems to be lateralized to the right temporal lobe region [1,19,44,45,52,67]. Neuro-imaging and Positron Emission Tomography (PET) studies have facilitated our knowledge of the localisation of spatial functions more precisely than has been possible with lesion studies in humans. In particular, hippocampal activation is associated with navigating in real or virtual world environments involving allocentric representation of the spatial domain [2,22,34–36].

Since in both the homing vector and route reproduction paradigms, a deficit occurred with the turn measures, this raises the question as to whether these two deficits are directly related. As indicated, above the lack of distance impairment in the homing vector test may indicate that the original turns had been encoded successfully. Also, the lack of turn reproduction impairment argues against a common problem with initial encoding. One possibility is that memory for direction is more vulnerable to impairment in the RTL patients, but this is only manifest with a more complex task that forces greater reliance on a longer-term memory representation. In the case of the homing vector test, the directional information might be calculated, but not...
retained. For the route reproduction measure, the turn is initially encoded, but lost later on, perhaps as the subject is reproducing the original route. Against this explanation is the finding that the directional error in path integration and the turn error for route reproduction did not correlate, suggesting that, at least in principle, these two components may be separable.

The neuronal basis for path integration is still a matter for speculation, despite the series of studies by Whishaw and colleagues that implicate the hippocampal formation (see introduction; [74,79]). The hippocampus is an obvious candidate, but these experiments have mostly involved FF lesions, so they do not provide direct evidence for hippocampal involvement. Indeed, the recent study by Aylan and McNaughton [4] suggested that neurotoxically hippocampectomized rodents are able to use path integration. This includes a foraging study in which the animal shuttles between two boxes along a tunnel equivalent to two sides of a triangular route. They then have to forage "underground" directly back to the starting place. The hippocampal rodents were as successful as control animals at returning directly to the start. In contrast, Maaswinkel et al. [33] tested rats with ibotenic lesions of the hippocampus on a foraging task involving the retrieval of pellets from an open field. The lesioned rats were impaired in their homing accuracy when only self-movement cues, not visual or surface cues, were available. In addition, Golob and Taube [24] measured the firing of head direction (HD) cells in rats with lesions to the hippocampus plus the overlying neocortex or to just the overlying neocortex. They found that these cells did not maintain a stable preferred firing direction (as they did in control rats) when the lesioned rat locomoted from a familiar to a novel environment, a process thought to require path integration. They concluded that the lesions led to an impairment in the path integration process. They further suggest that head direction cells may be used to compute the directional component of path integration and not the linear component. The linear component of path integration is thought unlikely to be represented by HD cells as these cells are only mildly influenced by linear velocity [69,70]. Thus, debate continues in the animal literature, as to whether it is the hippocampal formation that is the crucial structure for path integration.

Based on work with rodents, McNaughton et al. [38] view self-motion as the basis for our internal representation of the environment, to which the position of landmarks (allocentric representations) becomes secondarily bound. In addition, there is recent evidence that deficits shown in past experiments with hippocampal lesioned rodents on navigational tasks such as the Morris Water Maze [46] may reflect a path-integration impairment, rather than an allocentric spatial memory impairment, as has previously been supposed [74]. In rodents, it has been difficult to separate these two processes, as experiments investigating allocentric processes have always involved movement, and thus have necessarily involved path integration processes. In humans, there have been a large number of studies investigating the role of the hippocampus in allocentric spatial memory [19,45,52,67]. In these paradigms, the subject is stationary, thereby eliminating any path integration processes. The exception is the study by Abrams et al. [1] (see also Ref. 44), which shows a very striking spatial memory impairment. Thus, unlike the older rodent studies of allocentric spatial memory, evidence for a human right hippocampal involvement in allocentric spatial memory is not challenged by these findings, and it remains plausible that the right hippocampal formation supports both path integration and allocentric spatial memory.

The nature of the path integration deficit following RTL remains to be clarified through future studies. In the current experiment, it was not possible to distinguish between the processing of different types of self-motion inputs. To determine whether the RTL impairments seen on our tasks can be accounted for by a deficit in the monitoring or processing of self-motion cues, further experimentation is needed using paradigms that isolate vestibular and somatosensory processing (e.g. use of passive rotations and translations, or active tasks on counter-rotating surfaces).

This study leads to a number of conclusions, but has also raised a number of speculative points. The current experiment indicates that unilateral temporal lobectomy is associated with impairment in spatial memory based on idiothetic, rather than visual, input. The precise neuroanatomical underpinning of this is not certain, but clearly, the operation involves removal of the anterior hippocampus and associated cortical regions, such as the perirhinal, entorhinal and parahippocampal regions. Determining a homing vector is impaired, and so is route reproduction, although these deficits were not correlated, raising the possibility of dissociable processes. Thus, it appears in humans with damage to the right temporal lobes that a path integration deficit may exist, in addition to the previously established allocentric spatial memory impairment. Some of the abilities that underpin path integration have been shown not to be impaired, including the ability to reproduce single turns and determine traversed distances. This, in turn, emphasizes the link between the mnemonic or integration aspects of path integration and the temporal lobes.

Acknowledgements

We would like to thank Celia Ajuba, Hazel Lillies and Brett Huckstep for their invaluable assistance in testing subjects, and Nanda Vythelingum, Dominic Worsley et al. [39 (2001) 452–464]
Grise and Lidia Lees for their technical support. We also thank Dr Janet Feigenbaum for her helpful comments on the design of this study, and Professor Ian Whishaw for his careful reading of this manuscript and his constructive comments.

References